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The Infall of Gas onto the Galactic Disk

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Abstract. Ongoing accretion of low-metallicity gas onto the disk is a natural prediction of semi-analytical Galactic chemical evolution models. This star formation fuel ameliorates the overproduction of metal-poor G- and K-dwarfs in the solar neighbourhood which otherwise plague so-called "closed-box" models of Galaxy evolution. Do High-Velocity Clouds (HVCs) represent the source of this necessary fuel? We know that HVCs provide an important clue as to the processes governing galaxy formation and evolution - what is less clear is whether their role lies more closely aligned with cosmology (as relics of the Local Group's formation) or star formation (as tidal debris from nearby disrupted dwarfs, or the waste byproducts of disk supernova-driven winds). I provide a summary of recent speculations as to the origins of HVCs, and highlight several future projects which will lead to a deeper understanding of the role they play in galaxy evolution.

1. Introduction

Analytical models of Galactic chemical evolution invariably demand the existence of infalling (near?) pristine gas onto the disk in order to avoid the overproduction of low-metallicity stars - the so-called G-dwarf problem (Flynn & Morell 1997). Larson (1972) first suggested that this requisite star formation fuel might be associated with the population of High-Velocity Clouds (HVCs) seen moving at anomalous velocities with respect to differential Galactic rotation (Wakker & van Woerden 1997). Modern state-of-the-art chemical evolution models retain the need for this infalling fuel (e.g. Chiappini et al. 1997), although most do not necessarily target the HVCs as the most likely culprit. Tosi (1988) suggests that infalling fuel more metal-rich than $\gtrsim 0.2\,Z_\odot$ violates the present-day disk abundance constraints provided by HII regions, an hypothesis we are exploring with updated dual-infall (halo+disk phases) models (Chiappini et al. 2002).

Independent of these Galactic fuel arguments, a natural byproduct of hierarchical clustering galaxy formation scenarios (such as the currently favoured ΛCDM) is that the halo of our Milky Way should be populated with ∼500 satellites (Klypin et al. 1999), and accretion of gas should continue (at some level) to the present-day (as in the aforementioned analytical models). This prediction is more than an order of magnitude discrepant with that actually observed (∼30 satellites). Blitz et al. (1999) and Braun & Burton (1999) have both recently

revived the classic hypothesis due to Verschuur (1969), suggesting that HVCs are Local Group interlopers. This Local Group Infall scenario is based upon the assumption that the gas we see as an HVC traces an underlying (dominant) dark matter halo.

Do HVCs represent the reservoir of star formation fuel predicted to exist by analytical and numerical simulations of galaxy formation? Are they cosmological relics, waste byproducts related to tidal disruption of neighbouring dwarf galaxies, or supernova-driven ejecta from the disk? Whether they be cosmological, or related to star formation processes, HVCs represent crucial, yet mysterious, ingredients of galaxy formation. Under the former, the HI component of HVCs would contribute on the order of 10^{11} $M_\odot$ to the Local Group, while the latter[1] would correspond to order 10^7 $M_\odot$ of HI in the halo.

In what follows, I present a summary of the present-day state-of-affairs in HVC research, highlighting several intriguing (if sometimes confusing and/or contradictory) pieces of the puzzle, and avenues of future research.

2. Weighing the Evidence

In terms of assessing the role played by HVCs - cosmological or Galactic structure[2] - there are numerous discriminants which can be employed to argue for or against either option. Unfortunately, virtually all of these discriminants are purely of an indirect nature in the sense that unless the property under discussion is highly extreme, its interpretation is subject to one or more caveats.

Examples of such indirect arguments include:

- *Kinematic Distribution*: While it is tempting to use the fact that the velocity dispersion of the HVC distribution function is lower in the Local Group (and Galactic) Standards of Rest than it is in the Local Standard of Rest (e.g. Blitz et al. 1999), to argue for an extragalactic HVC residency, Gibson et al. (2001a) have shown that this is argument is specious.

- *Size-Linewidth Relationship*: Combes & Charmandaris (2000) note that Galactic halo HVCs adhere to the molecular cloud size-linewidth relationship, and if the Braun & Burton (1999) Compact HVCs were at 20 kpc they would also follow this relationship. While possibly correct, this argument (by itself) is also specious (Gibson et al. 2001b).

- *Connection to Local Star Formation*: An unappreciated clue to the HVC puzzle is provided by the work of Schulman et al. (1997). Their VLA analysis of isolated spirals shows that the incidence of HVC activity is directly related to the magnitude of underlying star formation in the galaxy's disk. This result is based upon only a handful of targets, but is not a prediction of the Blitz et al. (1999) model.

[1] Assuming typical distances of 4 kpc, and the integrated HI flux density from Table 3 of Wakker & van Woerden 1991.

[2] In reality, there is certainly a continuum of HVC populations; in fact, I would be surprised if there were not (c.f. Blitz 2001).

- *Local Group Analogs*: To date, extensive HI mapping of nearby Local Group analogs has not turned up evidence for extragalactic HVCs in these systems (Zwaan 2001). Similarly, the statistics of MgII and Lyman Limit absorbers in the spectra of background QSOs are in disagreement with the extragalactic HVC scenarios (Charlton et al. 2000). By definition, these other groups are not the Local Group (of course!), but unless one argues that the Local Group is somehow privileged, it is difficult to escape the obvious implications (c.f. Blitz 2001).

- *Metallicities*: HVC metallicities offer a potentially useful discriminant between competing theories for their origin. Very low metallicities ($\lesssim 0.01\,Z_\odot$) would argue against a recent Galactic disk event (such as a fountain), and support the Local Group building block scenarios of Blitz et al. (1999) and Braun & Burton (1999). Conversely, very high metallicities ($\gtrsim Z_\odot$) would be consistent with a Galactic fountain, but incompatible with the infalling star formation fuel hypothesis (recall the metalllicity argument of Tosi 1988). It should not be surprising to read that the interpretation of intermediate metallicities would be somewhat more contentious!

  To date, there are only a few HVCs for which accurate metallicities exist - none show evidence for metallicities below $0.1\,Z_\odot$, but neither do any show evidence for metallicities above $0.5\,Z_\odot$ (Gibson et al. 2001b,c; Wakker 2001). In fact, only one HVC has been claimed to have a metallicity $\lesssim 0.2\,Z_\odot$ - Complex C (Wakker et al. 1999). Gibson et al. (2001c) have shown though that Complex C is not the simple $0.1\,Z_\odot$ cloud that Wakker et al. thought it was. In fact, along one of the sightlines (Mrk 817), the sulfur and oxygen abundances are clearly in excess of $\gtrsim 0.2\,Z_\odot$. Recall, that both elements are depleted only lightly onto dust and the ionisation corrections for both OI and SII are (effectively) impervious to ionisation corrections. In other words, the metallicity determinations along these sightlines are robust (modulo HI column density normalisation, derived from lower spatial resolution 21cm data). Adopting the most recent solar system abundance normalisation increases the inferred oxygen abundance for the Mrk 817 sightline to $0.31\,Z_\odot$ (Gibson et al. 2001c).

  Taken together, it is tempting to suggest that virtually all HVCs have metallicities in the narrow range $0.2 \lesssim Z_\odot \lesssim 0.3$. At face value, this is the metallicity one would expect a priori for tidally-disrupted debris from the Large or Small Magellanic Clouds (Gibson et al. 2000) *or* from disk gas which originated at Galactocentric distances in excess of $\sim 1.5\,r_\odot$ (Gibson et al. 2001b; Figure 2b). *If* disk gas could be diluted in metallicity by a factor of ~ 2 during its putative passage through the halo even inner disk gas could be the ultimate source of HVCs.

  Interpreting the known HVC metallicities is difficult. While we can apparently rule out simple, undiluted, Galactic fountains, we can also rule out the failed dwarf/Local Group formation remnant scenario (recall Figure 1 of Gibson et al. 2001b) as all HVCs appear to be at least $10-30\times$ more metal-rich than the Local Group dwarf spheroidals.

- *Connection to Galactic Gas*: A danger with using digital tables of HVC properties (such as Wakker & van Woerden 1991 and Putman et al 2002)

is that the user may not appreciate that arbitrary cuts in $v_{\rm LSR}$ may mask sinuous connections to low-velocity Galactic gas. As Cohen (1981) and Putman & Gibson (1999) have shown, such connections are not uncommon and clearly show that some HVCs are most definitely of a Galactic nature. Of course, this argument is not valid for *all* HVCs.

- *Alternatives to ΛCDM*: Perhaps the simplest way in which to eliminate any discrepancy between the predictions for ΛCDM satellite counts versus those observed is not to associate HVCs with the ΛCDM halos, but to find a way to hide the halo baryons or eliminate the halos altogether. The former might include efficient feedback and/or photoionisation at high-redshift (Bullock et al. 2000; Chiu et al. 2001; Somerville 2001), while the latter might include variants to ΛCDM itself, such as Warm Darm Matter (Knebe et al. 2001), Self-Interacting Dark Matter (Davé et al. 2001), or Tilted Cold Dark Matter (Bullock 2001). The theorist in me enjoys the fevered investigations into CDM alternatives, while the observer remains ever skeptical ...

There is really only one *pure* discriminant between these extra-Galactic and Galactic scenarios - knowledge of the distance to the population of HVCs. Unfortunately, the distances to all but a few HVCs are unknown. Doubly unfortunate is the fact that there is really only one way to derive an unequivocal HVC distance - the detection of the cloud in absorption against a background halo star of known distance.

- *Absorption Line Distances*: Seen in absorption against a range of blue halo stars, five HVCs clearly reside in the halo (Gibson et al. 2001a; Table 1). Of course, this technique can *only* be applied to clouds in the halo - even if a given HVC did reside outside the halo, there would be no sufficiently bright background star to use as the probe of the intervening cloud. Clearly these five HVCs are inconsistent with the Local Group Infall models of Blitz et al. (1999) and Braun & Burton (1999).

Because of the difficulty in applying the absorption line distance technique, a number of indirect distance determinants have been proposed, including:

- *Hα Distances*: Under the (reasonable) assumption that $\gtrsim$1% of the disk's ionising escape into the halo, coupled with a model describing the photon sources' distribution, as well as some knowledge of the covering fraction, topology, and line-of-sight orientation of a given HI screen, the measured Hα emission measure from the screen can be inverted to provide a distance. The halo ionising radiation field model of Bland-Hawthorn et al. (1999,2001) is generally adopted; practical applications of the technique have been demonstrated by Bland-Hawthorn et al. (1998), Tufte et al. (1998), and Weiner et al. (2001). The technique has received a great deal of attention due to its potential application across a large fraction of the HVC population; that said, it has also been one of the more contentious issues in the field! Many of its shortcomings appear to have been rectified by the recent inclusion of spiral arms into the underlying disk model (Bland-Hawthorn et al. 2001). Weiner et al. (2001) suggest that the extant data is inconsistent with the Blitz et al. (1999) Local Group Infall model.

- *Head-Tail Substructure*: $\sim$20% of Compact HVCs show distinct head-tail structure, suggestive of interaction with an external medium. Quilis & Moore (2001) show that an ambient density in excess of $\sim 10^{-4}\,\mathrm{cm}^{-3}$ is required to shape these clouds. Such densities are consistent with an upper halo location, but *not* an intergalactic one. That said, this argument only applies to a subset of HVCs.

- *Pressure Arguments*: Burton et al. (2001) employ thermal pressure arguments applied to Compact HVCs to claim that HVCs lie at distances of 400 ± 280 kpc. As pointed out by Amiel Sternberg (cited in Gibson et al. 2001b), this result should strictly be interpreted as an upper limit (and not an equality), since Burton et al. only adopt the minimum pressure necessary to maintain the observed core/halo interface (as opposed to the range allowed by a multiphased mixture).

- *Cohen Stream*: The Cohen Stream (HVC 165$-$43$-$120), part of the Anti-Centre High-Velocity complex mapped in HI by Cohen (1981), spans 25° on the sky. This -120 km/s feature is not seen in Hα, but it does trace a parallel HI filament at -13 km/s, and so must be at a distance $\lesssim$300 pc.

- *Search for Stars in HVCs*: The search for stars within HVCs (and especially Compact HVCs) has begun in earnest. Programs are underway at LCO/KPNO (Grebel et al. 2000), the Sloan Digital Sky Survey (Willman et al. 2002), and via the use of archival POSS-II plates (Simon & Blitz 2002, in preparation) - to date, none of these studies have uncovered a stellar population associated with any HVC. A primary motivation for this work is the search for an excess of potential red giant branch tip stars (useful distance diagnostics) and (perhaps) even RR Lyrae.

3. The Future

An enormous effort is underway to map stellar sub-structure in the halo, and use this information to reconstruct the detailed physics governing the formation of the Milky Way (e.g. Ibata et al. 2001; Morrison et al. 2000; Helmi et al. 1999; Willman et al. 2002). It is crucial to remember that the halo is populated by not only stars, but a not insignificant reservoir of gas. This gas distribution needs to be painstakingly mapped, its origin(s) assessed, and the relevant physics explored - whether this physics is more aligned with cosmology or star formation is yet to be definitively demonstrated, but does *not* change the fact that HVCs are important clues to galaxy formation *and/or* galaxy evolution! *Halo gas tomography* is the most pressing area of HVC research.

With Mike Bessell, Tim Beers, Norbert Christlieb, and Joss Bland-Hawthorn, we have embarked on a long-term program using the 6dF Facility at the United Kingdom Schmidt Telescope to identify large numbers of suitable (distant) halo probes aligned with (potenially) foreground HVCs. Full three-dimensional mapping of halo HVCs is our ultimate goal. In conjunction with the stellar tomography provided by satellites such as FAME, DIVA, and (especially) GAIA, halo gas tomography will provide the ingredients necessary to undertake full baryonic reconstructions of the halo's formation. These tests of *near-field cosmology* are

poised to compete on an equal level with *far-field cosmology* over the coming decade.

High-resolution N-body and hydrodynamical simulations of both the interaction of HVCs with the Galaxy, and the Local Group's formation, must continue for the foreseeable future. As Quilis & Moore (2001) demonstrate, there is much yet to be learned. With Daisuke Kawata, for example, we have been attempting to simulate the spatial and kinematic properties of Complex C using satellite perturbers (as a sort of "straw man" model) interacting with the Outer Arm of the Milky Way's disk. We have actually been (reasonably!) successful in doing so, generating one realisation in which Complex C gas originated from within the disk (at $\sim 2\,r_\odot$), but from the opposite side of the Galaxy. Gas was drawn from the disk by the close passage of the perturber and "pulled" over the Galaxy in its wake, to find itself now infalling onto the disk in the vicinity of the Outer Arm at $\ell \sim 90^\circ$. The spatial, kinematical, and metallicity properties of Complex C are all recovered![3] In addition, we are pursuing very high mass resolution sticky-particle simulations of the Local Group's formation with Kenji Bekki.

The availability of STIS and (soon) COS on HST, as well as FUSE, means that a concerted effort needs to be made in continuing to obtain metallicities and ionisation conditions of HVCs (and IVCs) using background QSO probes. Time Allocation Committees need to be made aware that not all HVCs are the same, and just because one or two clouds have well-determined metallicities does not mean that therefore all clouds have now been sampled! We have been successful in obtaining FUSE Cycle 2 time to study the anti-Local Group barycentre HVC 246+39+125, and have recently been awarded HST/STIS Cycle 11 time to study the Compact HVC 225−83−197 (to supplement our extant FUSE data on this sightline). Cloud abundance patterns remain a powerful tool for disentangling different origins scenarios (and determining the nucleosynthetic pollution history - e.g. have these clouds seen pollution from Type II or Type Ia supernovae?). Despite these successes, it is most definitely a challenge to convince TACs that HVCs are important clues to the formation mechanisms of galaxies!

Further searches for HVCs in nearby Local Group analogues must continue, as the initial results from Zwaan (2001) have been so intriguing. With D.J. Pisano, David Barnes, and Lister Staveley-Smith, we are using the narrowband filters with the mulitbeam facility at Parkes to Nyquist sample $\sim 1\,\mathrm{Mpc}^2$ around Local Group "clones" to an HI mass sensitivity of $3\times 10^6\,\mathrm{M}_\odot$ (5σ). With Bärbel Koribalski, we are surveying (to a comparable sensitivity limit) an ~ 100 sq.deg region of the Supergalactic Plane in the vicinity of the HVC (protogalaxy?) discovered by Kilborn et al. (2000), in order to search for low-level extended emission.

On an even more ambitious level, with Frank Briggs, Martin Zwaan, David Barnes, et al., we have been awarded 14 nights at Parkes as a pilot study to what we call HIPARK - a parked, transit-style, Parkes, survey. Ultimately, our goal is

[3] At the expense of doing some substantial damage to the gas disk in the inner regions of the Milky Way, but we'll sweep that under the rug for another day (Gibson & Kawata 2001, in preparation)!

to drift-scan the same ($\sim$100 sq.deg) strip of sky over a continuous three-month period, down to a 6σ limiting HI mass of $3{\times}10^4\,\mathrm{M}_\odot$ (at 1 Mpc)![4]

Finally, a concerted effort must be made to either find stars associated with HVCs (they are enriched in metals, and if they are at Local Group-like distances, they almost certainly had to acquire those metals internally through star formation) or definitively refute their existence (which would argue for them being local, and enriched from their parent galaxy, whether that was the Milky Way, LMC, SMC, or some other disrupted dwarf). Many Time Allocation Committees have recognised the value of these searches, but that is most definitely not a universal sentiment! Deep wide-field imaging of a statistically significant number of Compact HVCs (and neighbouring blank sky) should be undertaken at 4-8m class facilities as soon as possible.

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[4] Or $3\,\mathrm{M}_\odot$ at 10 kpc!

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